QCD spin physics - a theoretical overview

Daniël Boer
Free University Amsterdam
(at RBRC: 10/1998-06/2001)

QCD spin physics is about defining and extracting universal nonperturbative quantities that capture aspects of the proton spin

polarized DIS $\longrightarrow$ quark helicity distributions $\longrightarrow$ polarized gluon distribution $\longrightarrow$ orbital angular momentum $\longrightarrow$ GPDs

single spin asymmetries $\longrightarrow$ TMDs $\longrightarrow$ Wigner distributions $\longrightarrow$ GPDs

Nick is right

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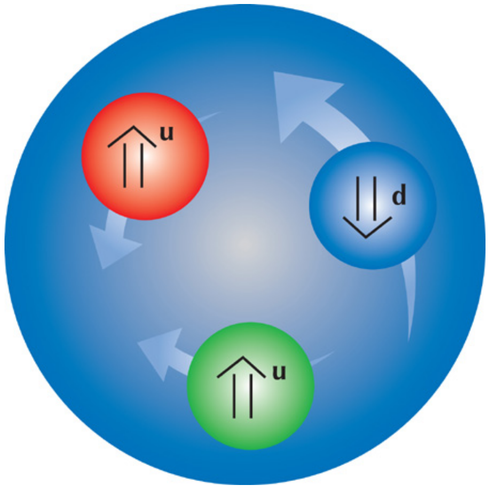
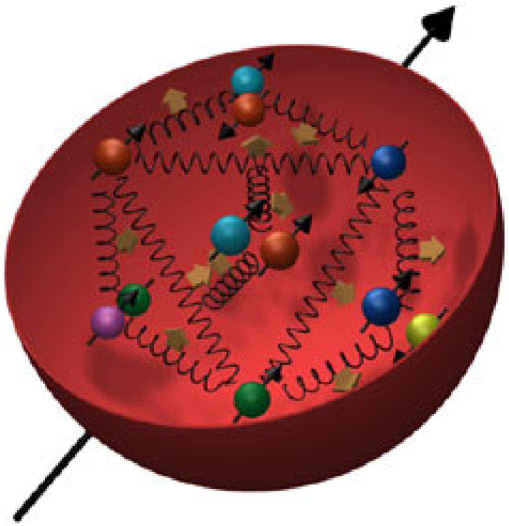
QCD spin physics

QCD spin physics = (to a large extent) the study of the spin of the proton expressed in terms of quark and gluon d.o.f.

How does a dynamical system of quarks and gluons yield a spin-1/2 proton?

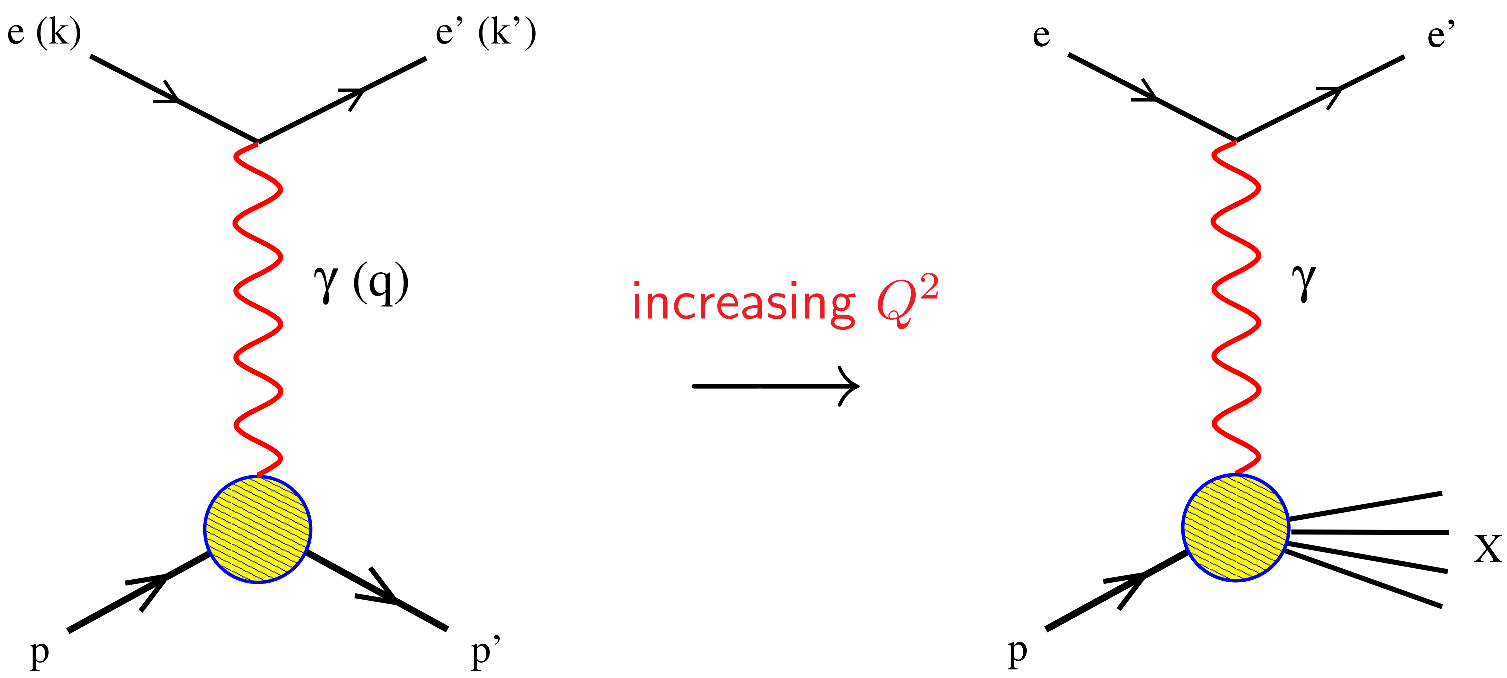




Quarks are confined inside hadrons, so one needs to scatter with high energy particles off hadrons to probe quark properties

As probes one can use electrons, muons, neutrinos, hadrons, ...

Elastic and inelastic Scattering



$$Q^2 = -q^2 = -(k' - k)^2$$

Elastic scattering (Q^2 small) probes form factors

Deep inelastic scattering (Q^2 large) probes structure functions and parton densities

QCD spin physics

Parton densities are hadronic matrix elements of some appropriate operator:

$$\langle P \,|\, \text{operator}(\overline{\psi}, \psi, A) \,|\, P \rangle$$

Goal: define and extract those operators that capture aspects of the proton spin

For example, $\Delta\Sigma$, the sum of quark contributions to the proton spin:

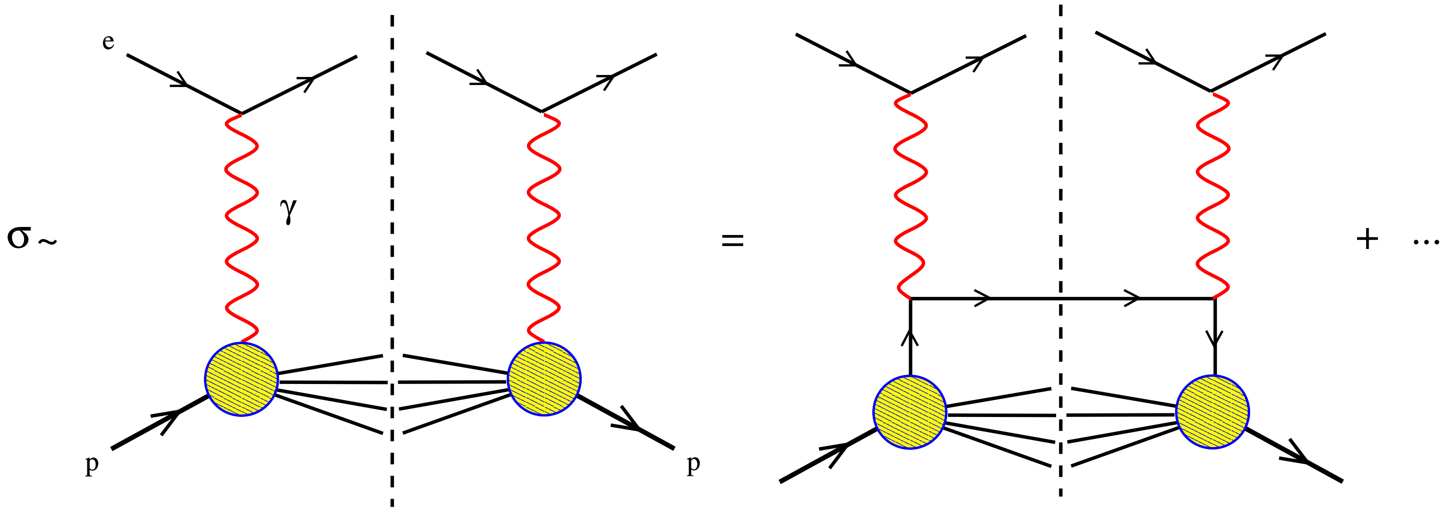
$$\begin{aligned} \Delta\Sigma &\equiv \Delta u + \Delta d + \Delta s \\ \Delta q &= (q_+ - q_-) + (\bar{q}_+ - \bar{q}_-) \end{aligned}$$

The operator matrix element (OME) definition of Δq is:

$$\langle P, S | \overline{\psi}_q \gamma^\mu \gamma_5 \psi_q(0) | P, S \rangle \sim \Delta q \, S^\mu$$

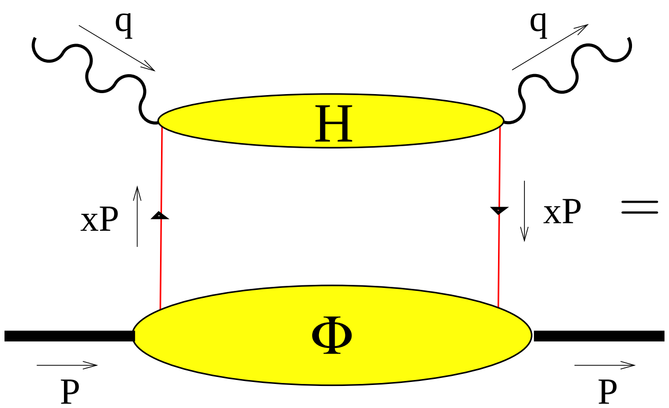
And it can be extracted from deep inelastic $\vec{e}\,\vec{p}$ scattering (GRSV, AAC, ...)

Factorization in deep inelastic scattering



If Q^2 is large enough, small QCD coupling allows for factorization of the cross section

$\sigma(\gamma^* p \to X) \propto$



$= \int dx\, \mathrm{Tr}\left[H(x;Q^2)\Phi(x;M^2)\right] + \mathcal{O}\left(1/Q^2\right)$

$x = p^+/P^+$ is the light-cone momentum fraction of a quark (p) inside a hadron (P)

Gauge invariant definition of OME

In DIS one encounters functions of lightcone momentum fractions

$$\Phi_{ij}(x) \quad = \quad \int \frac{d\lambda}{2\pi}\, e^{i\lambda x}\, \langle P,S|\, \overline{\psi}_j(0)\, \mathcal{L}[0,\lambda]\, \psi_i(\lambda n_-)\, |P,S\rangle \qquad ({n_-}^2 = 0)$$

$\Phi(x)$: operator matrix element (OME) of a nonlocal lightcone operator

$$\mathcal{L}[0,\lambda] = \mathcal{P}\exp\left(-ig\int_0^\lambda d\eta\, A^+(\eta n_-)\right) \xrightarrow{A^+=0} 1$$

Such a path-ordered exponential (link) not just inserted, but can be *derived*

Efremov & Radyushkin, Theor. Math. Phys. 44 (1981) 774

Mellin moments: $\displaystyle \int dx\, x^N\, \Phi(x) \quad \longrightarrow$ local operators

Parton distribution functions

In general, one has

$$\Phi(x) \;=\; \frac{1}{2}\left[f_1(x)\, \not{P} + g_1(x)\, \lambda\gamma_5 \not{P} + h_1(x)\, \gamma_5 \not{S}_T \not{P}\right] + \text{higher twist functions}$$

Often one also writes $f_1^q(x) = q(x)$, $g_1^q(x) = \Delta q(x)$, $h_1^q(x) = \delta q(x)$

$$\begin{aligned} \Delta q &= \int dx\, g_1^q(x) \sim \int dx \,\mathrm{Tr}\left(\Phi(x)\gamma^+\gamma_5\right) \sim \langle P, S \,|\, \overline{\psi}_q \gamma^+ \gamma_5 \psi_q(0) \,|\, P, S\rangle \\ &= \text{density of righthanded quarks - lefthanded} \end{aligned}$$

Very nice!

We have a definition of the quark helicity distribution Δq *and* a method of extracting it experimentally

However...

$\Delta\Sigma$

$\Delta\Sigma$ as extracted from experiment turns out to be much smaller than expected

European Muon Collaboration [1988] ($\langle Q^2 \rangle = 10.75$ GeV^2): $\Delta\Sigma = 0.00 \pm 0.24$

Spin Muon Collaboration [1998] ($Q^2 = 5$ GeV^2): $\Delta\Sigma = 0.13 \pm 0.17$

It means that the quarks and antiquarks contribute almost nothing to the proton spin!

This was dubbed the "spin crisis" or "spin puzzle"

Spin sum rule

In general, one expects the following "spin sum rule" to hold

$$\text{proton spin } = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta g + L_z$$

$$\Delta g = \int dx\, \Delta g(x) = \int dx\, [g_+ - g_-]$$

The unintegrated polarized gluon distribution is defined as

$$\Delta g(x) = \frac{i}{4\pi x (P^+)^2} \,\text{F.T.}\, \langle P, S_L \,|\, F^{+\alpha}(0)\, \mathcal{L}[0,\lambda]\, \tilde{F}_\alpha{}^{+}(\lambda n_-) \,|\, P, S_L \rangle$$

This means that $\int dx\, \Delta g(x)$ is intrinsically nonlocal along the lightcone

It becomes local (in $A^+ = 0$ gauge) only after a tricky partial integration

Nonlocal operators are difficult to model or to calculate using the lattice

Δg and L_z

At present $\Delta g(x)$ is under active experimental investigation:

- polarized $p\,p$ collisions at RHIC (2005 data at $\sqrt{s} = 200$ GeV indicates $\Delta g(x) \ll g(x)$)
- polarized DIS at CERN (COMPASS)

Measuring Δg and using the spin sum rule, yields information about the size of L_z

Natural question: is $L_z = L_z^q + L_z^g$?

Appears not to be the case, unless one chooses a specific gauge or a specific frame

Bashinsky, Jaffe, NPB 536 (1998) 303: gauge invariant, frame dependent decomposition

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta g + L_q + L_g$$

No known way of accessing these L_q, L_g experimentally

Orbital angular momentum of quarks

Another gauge invariant decomposition has been considered:

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + J_g$$

$$\vec{J}_q = \int d^3x \left[\psi^\dagger \frac{\vec{\Sigma}}{2}\psi + \psi^\dagger \vec{x} \times (-i\vec{D})\psi\right]$$

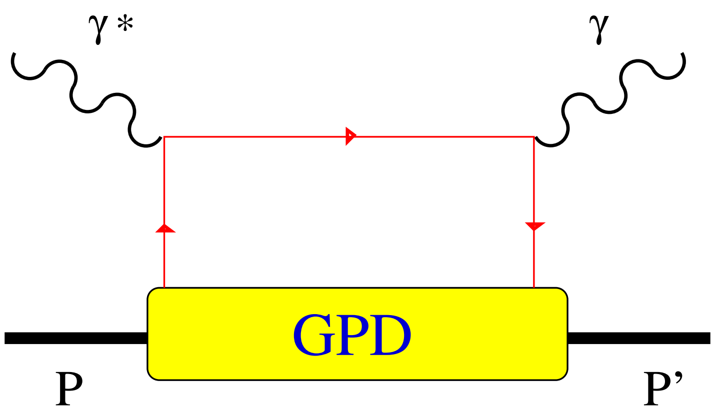
$$\vec{J}_g = \int d^3x \left[\vec{x} \times (\vec{E} \times \vec{B})\right]$$

$$\langle P, S|\vec{J}_{q,g}|P, S\rangle \propto J_{q,g}(Q^2)\vec{S}$$

Leads to a similar question: $J_g = \Delta g + L_g$?

To get a handle on orbital angular momentum of quarks $L_q(x)$, Xiangdong Ji proposed (PRL 78 (1997) 610) to use Deeply Virtual Compton Scattering: $\gamma^* + p \rightarrow \gamma + p'$

DVCS



This involves off-forward, lightcone OMEs

Generalized Parton Distributions

$$\int \frac{d\lambda}{2\pi} e^{i\lambda x} \langle P' | \, \overline{\psi}(-\lambda/2) \, \gamma^+ \mathcal{L}[-\lambda/2, \lambda/2] \, \psi(\lambda/2) \, | P \rangle =$$

$$H_q(x,\xi,t) \, \bar{u}(P')\gamma^+ u(P) + E_q(x,\xi,t) \, \bar{u}(P') \frac{i\sigma^{+\nu}\Delta_\nu}{2M_N} u(P)$$

with $\Delta = P' - P$, $\xi = -\Delta^+/(P'^+ + P^+)$ and $t = \Delta^2$

Forward limit: $H_q(x,0,0) = q(x)$, $\quad E_q(x,0,0) \equiv E_q(x)$

$E_q(x)$ is not accessible in DIS

Generalized parton distributions

Orbital angular momentum of quarks defined as (Hoodbhoy, Ji, Lu, PRD 59 (1999) 014013):

$$L_q(x) = \frac{1}{2}\left[xq(x) + xE_q(x) - \Delta q(x)\right]$$

Going from GPDs to L_q is very hard (extrapolations)

Hence, OAM is not straightforward to define and measuring it is even less trivial

But GPDs have become of interest in their own right, beyond OAM

GPDs yield a more complete picture of momentum *and* spatial distributions of partons

Burkardt, PRD 62 (2000) 071503; hep-ph/0207047

Belitsky & Müller, hep-ph/0206306

Diehl, EPJC 25 (2002) 223

Transverse polarization

For a transversely polarized proton a tensor charge can be defined:

$$\langle P,S|\overline{\psi}_q \sigma^{\mu\nu}\gamma_5 \psi_q(0)|P,S\rangle \sim \delta q\ [P^\mu S^\nu - P^\nu S^\mu]$$

$$\delta q = \int dx\, h_1^q(x) \qquad h_1(x) \text{ is called transversity}$$

Difficult, but not impossible, to measure; many proposals have been put forward

Not measurable in elastic scattering or in inclusive deep inelastic scattering

However, $h_1(x)$ can be probed by using other hadrons: e.g. in $e\,p^\uparrow \to e'\,\pi\,X$ or $p^\uparrow\,p^\uparrow$

h_1 contains completely new information on the proton spin structure

Realistic extractions can come from BELLE+RHIC data (using interference fragmentation functions) or from future GSI/FAIR $p^\uparrow\,\bar{p}^\uparrow$ data

What is known about the size of δq?

Thus far δq has only been studied in models and using lattice QCD

First (quenched) lattice QCD determination yielded (at $\mu^2 = 2$ GeV^2):

$$\delta u = +0.839(60), \quad \delta d = -0.321(55), \quad \delta s = -0.046(34)$$

S. Aoki *et al.*, PRD 56 (1997) 433

See also: Orginos, Blum, Ohta, hep-lat/0505023

Most recent lattice determination (with dynamical quarks) obtained (at $\mu^2 = 4$ GeV^2):

$$\delta u = 0.857 \pm 0.013, \quad \delta d = -0.212 \pm 0.005$$

QCDSF and UKQCD Collab., Göckeler *et al.*, PLB 627 (2005) 113

Most models find results roughly in the range:

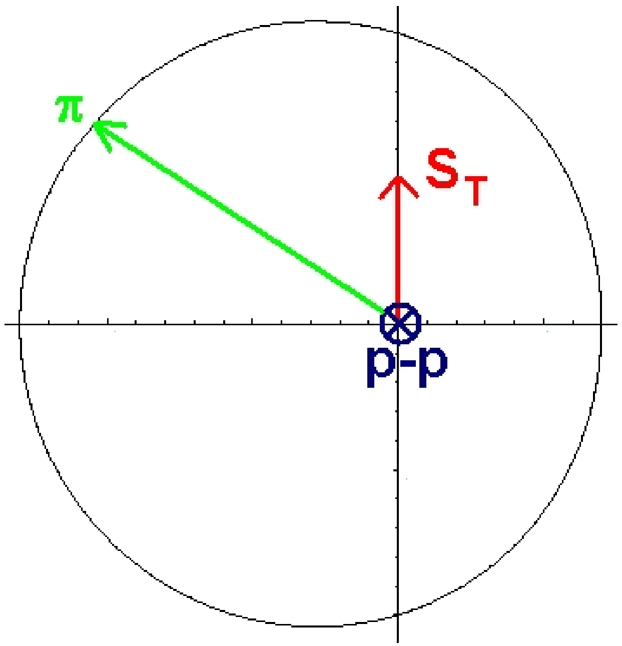
$$\delta u = +1.0 \pm 0.2, \quad \delta d = -0.2 \pm 0.2$$

Left-right asymmetries

Transverse polarization has another trick up its sleeve...

Large single spin asymmetries in $p\,p^{\uparrow} \to \pi\,X$ have been observed

E704 Collab. ('91); AGS ('99); STAR ('02); BRAHMS ('05); ...



A left-right asymmetry

Pion distribution is asymmetric depending on transverse spin direction and on pion charge

What is the explanation at the quark-gluon level?

Clearly a spin-orbit coupling, but how to describe such effects?

Transverse momentum of quarks

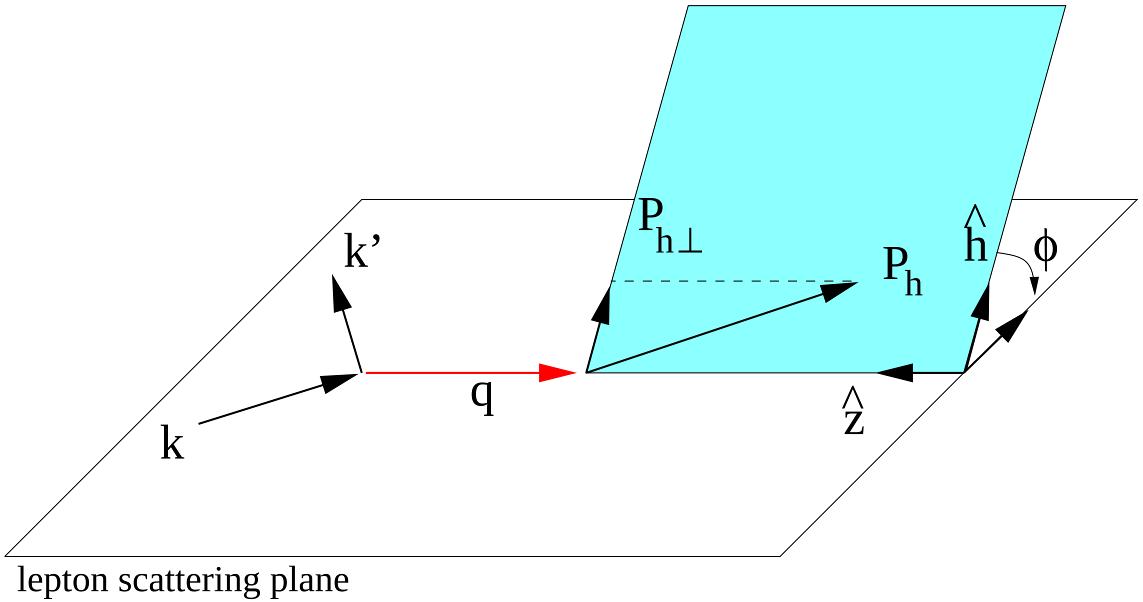
OAM requires transverse momentum of the quarks inside a hadron

Natural, but highly nontrivial, extension of $\Phi(x) \to \Phi(x, \boldsymbol{k}_T)$
Soper '77; Ralston & Soper '79; many others

$\Phi(x, \boldsymbol{k}_T)$ can be probed in experiments, for instance in semi-inclusive DIS

SIDIS

$e\,p \to e'\,\pi\,X$



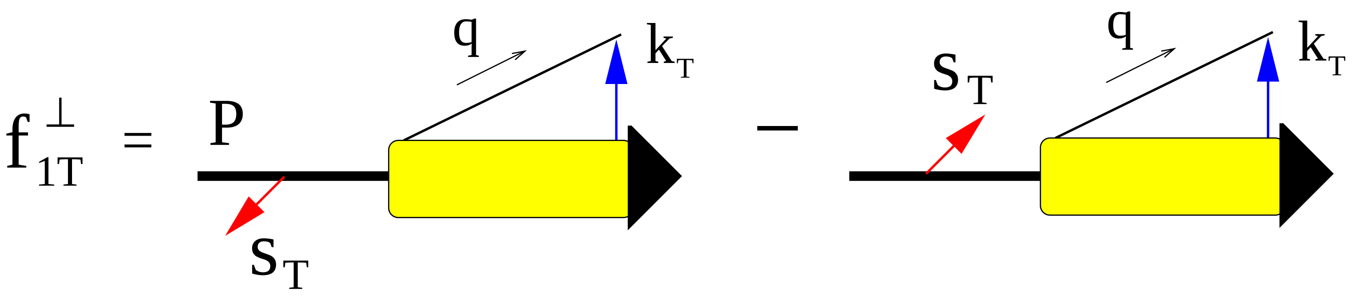
A multiscale process: $M, |\boldsymbol{P}_\perp^\pi|$ and Q with $|\boldsymbol{P}_\perp^\pi|^2 \ll Q^2$

Spin dependent TMDs

TMD = transverse momentum dependent parton distribution function

$$\Phi(x, \boldsymbol{k}_T) = \frac{1}{2}\, f_1(x, \boldsymbol{k}_T^2)\, \not{P} + \frac{\boldsymbol{P}\cdot(\boldsymbol{k}_T \times \boldsymbol{S}_T)}{2M}\, f_{1T}^{\perp}(x, \boldsymbol{k}_T^2)\, \not{P} + \ldots$$

Upon integration over transverse momentum the Sivers function $f_{1T}^{\perp}$ drops out



Sivers, PRD 41 (1990) 83

The Sivers effect leads to various single spin asymmetries, which are being tested at several labs (BNL, CERN, DESY, Jefferson Lab)

Measuring the Sivers effect: two examples

One can probe the k_T-dependence of the Sivers function directly in "jet SIDIS"

$$\frac{d\sigma(e\,p^{\uparrow} \to e'\,\text{jet}\,X)}{d\phi^e_{\text{jet}}\,dk_T^2} \propto |\boldsymbol{S}_T|\,\sin(\phi^e_{\text{jet}} - \phi^e_S)\,\frac{k_T}{M} f_{1T}^{\perp}(x, k_T^2), \qquad k_T^2 = |\boldsymbol{P}_{\perp}^{\text{jet}}|^2$$

D.B. & Mulders, PRD 57 (1998) 5780

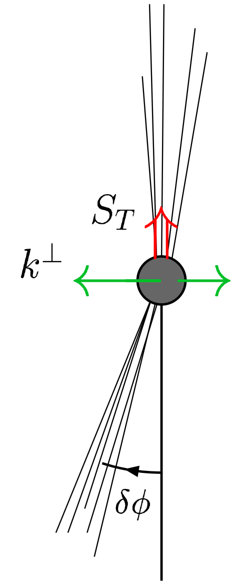
Upon integration over the transverse momentum of the jet: no SSA remains

Christ & Lee, PR 143 (1966) 1310

Asymmetric jet or hadron correlations in $p^{\uparrow}\,p \to h_1\,h_2\,X$

D.B. & Vogelsang, PRD 69 (2004) 094025

Bacchetta *et al.*, PRD 72 (2005) 034030



Link structure of TMDs

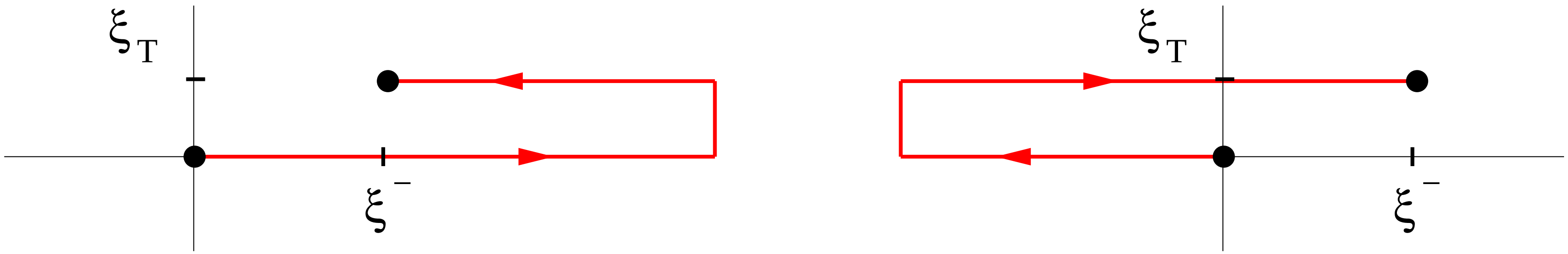
At first sight a $\boldsymbol{P}\cdot(\boldsymbol{k}_T \times \boldsymbol{S}_T)$ correlation appears to violate time reversal invariance
Collins, NPB 396 (1993) 161

But a model calculation by Brodsky, Hwang, Schmidt (PLB 530 (2002) 99) implied otherwise

$\Phi(x, \boldsymbol{k}_T)$ is a matrix element of operators that are nonlocal *off* the lightcone

$$\Phi(x, \boldsymbol{k}_T) = \text{F.T.}\, \langle P|\, \overline{\psi}(0)\, \mathcal{L}[0,\xi]\, \psi(\xi)\, |P\rangle\Big|_{\xi=(\xi^-,0^+,\boldsymbol{\xi}_T)}$$

In SIDIS one has a future pointing Wilson line, whereas in Drell-Yan a past pointing one



In lightcone gauge $A^+ = 0$ the piece at infinity is crucial

Belitsky, Ji & Yuan, NPB 656 (2003) 165

Process dependence of TMDs

As a consequence there is a *calculable* process dependence (Collins, PLB 536 (2002) 43):

$$(f_{1T}^{\perp})_{\rm DIS} \quad = \quad -(f_{1T}^{\perp})_{\rm DY}$$

The color flow of a process is crucial for the link structure
The more hadrons are observed, the more complicated the link structure
Bomhof, Mulders & Pijlman, PLB 596 (2004) 277; hep-ph/0601171

This is a new feature and factorization theorem proofs need to be revisited

Factorization theorems for processes involving a small transverse momentum
Collins & Soper, NPB 193 (1981) 381
Ji, Ma & Yuan, PRD 71 (2005) 034005; PLB 597 (2004) 299

Other consequences of the link structure

The link structure leads to intrinsically nonlocal lightcone OME

Taking $A^+ = 0$ or taking Mellin moments does *not* yield local OMEs

For example,

$$f_{1T}^{\perp(1)}(x) \equiv \int d^2\boldsymbol{k}_T \frac{\boldsymbol{k}_T^2}{2M^2} f_{1T}^{\perp}(x, \boldsymbol{k}_T^2) \overset{A^+=0}{\propto} \langle\, \overline{\psi}(0) \int d\eta^-\ F^{+\alpha}(\eta^-)\ \gamma^+\, \psi(\xi^-)\ \rangle$$

Hard to interpret or to evaluate using models or the lattice

Theoretically the energy scale (Q^2) dependence poses questions still
Very involved; not leading twist operators in the OPE sense
Henneman, D.B. & Mulders, NPB 620 (2002) 331

Wigner distributions

A relation between $f_{1T}^{\perp(1)}$ and the GPD E has been put forward

Burkardt, hep-ph/0302144; Burkardt & Hwang, hep-ph/0309072

$$f_{1T}^{\perp(1)}(x) \propto \epsilon_T^{ij} S_{Ti} \int d^2\boldsymbol{b}_\perp \boldsymbol{I}(\boldsymbol{b}_\perp) \frac{\partial}{\partial b_\perp^j} E(x, \boldsymbol{b}_\perp)$$

The factor $\boldsymbol{I}(\boldsymbol{b}_\perp)$ not analytically calculable, has to be modeled, limits the use

GPDs and TMDs viewed as reductions of quantum phase-space (Wigner) distributions

$$W_\Gamma(\vec{r}, k) \equiv \frac{1}{2M_N} \int \frac{d^3q}{(2\pi)^3}\, e^{-i\vec{q}\cdot\vec{r}}\, \langle \vec{q}/2 |\, \hat{\mathcal{W}}_\Gamma(k)\, | -\vec{q}/2 \rangle$$

$$\hat{\mathcal{W}}_\Gamma(k) = \int d^4\eta\, e^{i\eta\cdot k}\, \overline{\Psi}(-\eta/2)\Gamma\Psi(\eta/2)$$

Ji, PRL 91 (2003) 062001; Belitsky, Ji & Yuan, PRD 69 (2004) 074014

Reductions of Wigner distributions

Fourier transforms of GPD's are obtained as follows:

$$\int \frac{d^2\boldsymbol{k}_T}{(2\pi)^2}\left[\int \frac{dk^-}{2\pi} W_{\gamma^+}(\vec{r},k)\right]$$

$$\propto \text{F.T.}\left\{H_q(x,\xi,t)\,\bar{u}(\vec{q}/2)\gamma^+ u(-\vec{q}/2) + E_q(x,\xi,t)\,\bar{u}(\vec{q}/2)\frac{i\sigma^{+i}q_i}{2M}u(-\vec{q}/2)\right\}$$

TMDs can also be seen as reductions of Wigner distributions

$$q(x,\boldsymbol{k}_T) = \int \frac{d^3r}{(2\pi)^3}\left[\int \frac{dk^-}{2\pi} W_{\gamma^+}(\vec{r},k)\right]$$

The six-dimensional phase space quantity: just a definition or measurable?

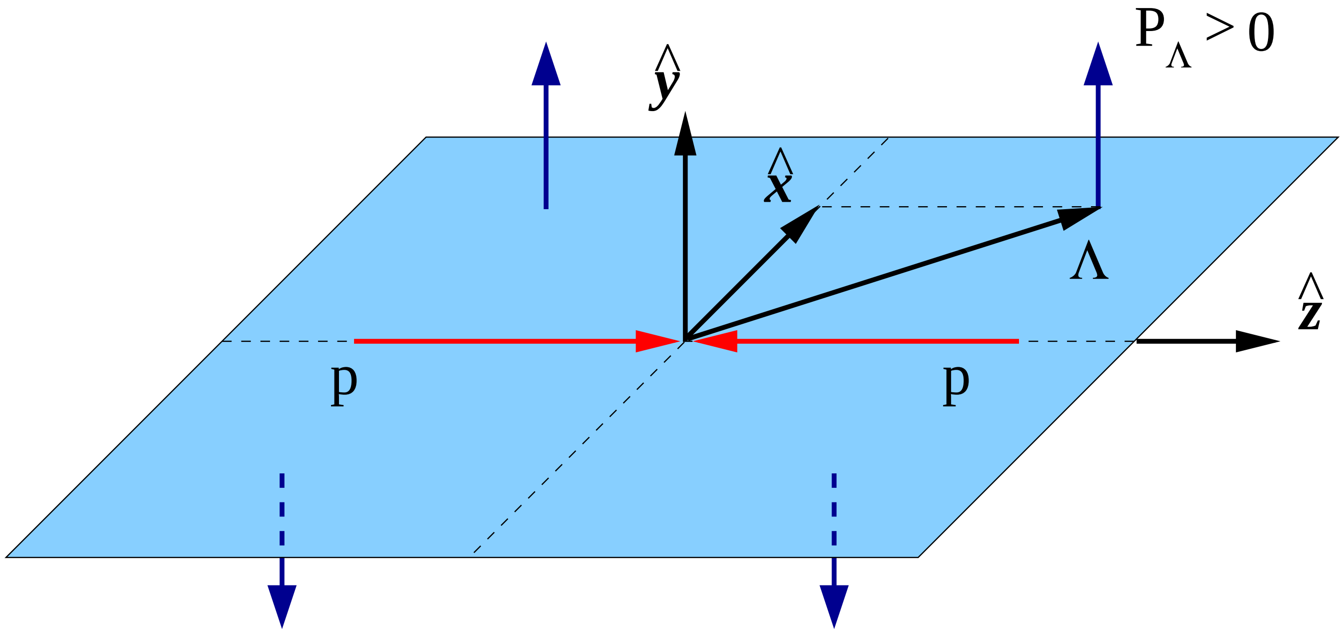
$$f_{\gamma^+}(\vec{r},x,\boldsymbol{k}_T) \equiv \int \frac{dk^-}{2\pi} W_{\gamma^+}(\vec{r},k)$$

Note: $\boldsymbol{k}_T$ and $\boldsymbol{r}_T$ are not each other's Fourier conjugates

Λ polarization from unpolarized scattering

Large asymmetries have been observed in $p + p \to \Lambda^{\uparrow} + X$

G. Bunce *et al.*, PRL 36 (1976) 1113; and by many others afterwards



The observed transverse polarization is negative (so opposite to the blue arrows)

The fragmentation analogue of the Sivers effect can describe such data ($p_T > 1$ GeV)

Anselmino, D.B., D'Alesio & Murgia, PRD 63 (2001) 054029

* How to measure Λ polarization *

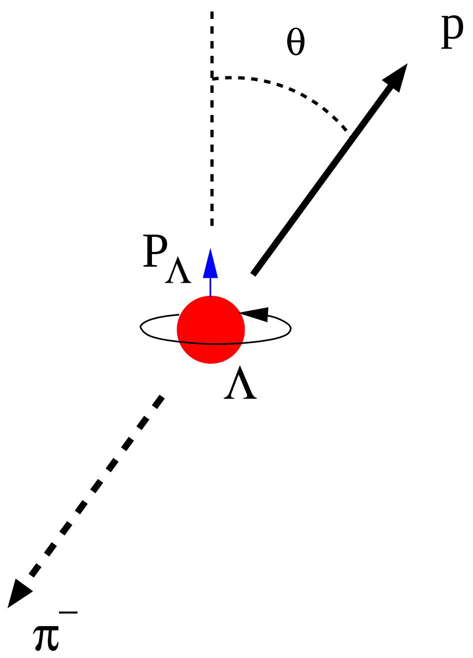
"Possible detection of parity nonconservation in hyperon decay"

T.D. Lee *et al.*, PR 106 (1957) 1367

"Possible Determination of the Spin of Λ^0 from its large Decay Angular Asymmetry"

T.D. Lee & C.N. Yang, PR 109 (1958) 1755

Λ polarization is "self-analyzing" due to parity violation



Proton distribution in Λ rest frame:

$$\frac{dN(p)}{d\cos\theta} = \frac{N_0}{2}(1 + \alpha_\Lambda P_\Lambda \cos\theta)$$

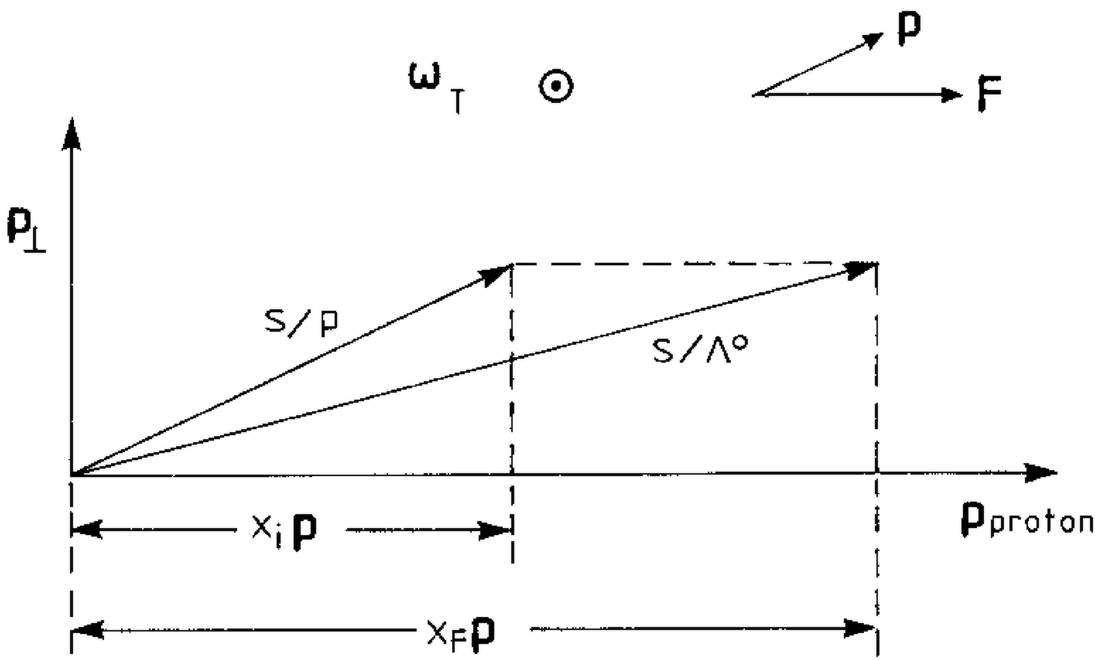
$P_\Lambda = \Lambda$ polarization

$\alpha_\Lambda = 0.64$

* Theoretical considerations *

Perturbative QCD conserves helicity, which leads to $P_\Lambda \sim \alpha_s m_q/\sqrt{\hat{s}}$ (= small)
Kane, Pumplin & Repko, PRL 41 (1978) 1689

Many QCD-inspired models have been proposed, mostly based on
recombination of a fast ud diquark from the proton and a slower s quark from the sea
Spin-orbit coupling creates the polarization



The DeGrand-Miettinen model
PRD 23 (1981) 1227 & 24 (1981) 2419

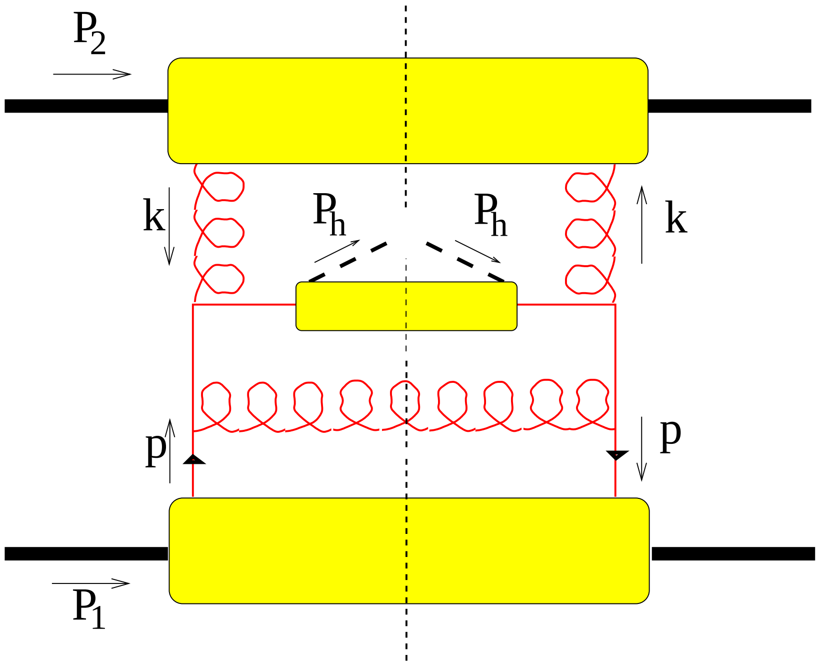
* Collinear factorization *

For large $\sqrt{s}$ and p_T factorization should apply; the process $p + p \rightarrow \Lambda + X$ should be described in terms of parton densities and a fragmentation function

$$\sigma \sim q(x_1) \otimes g(x_2) \otimes D_{\Lambda/q}(z)$$

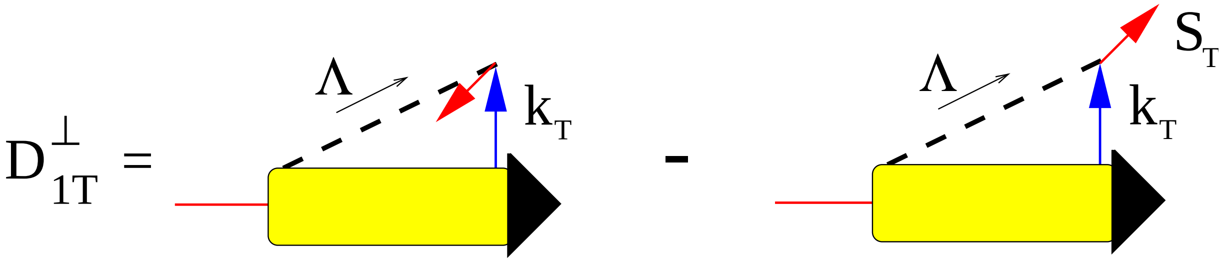
$$q(x_1) = \text{quark density}$$
$$g(x_2) = \text{gluon density}$$
$$D_{\Lambda/q}(z) = \Lambda \text{ fragmentation function}$$

$$P_\Lambda \sim q(x_1) \otimes g(x_2) \otimes ?$$



Problem: no fragmentation function exists for $q \rightarrow \Lambda^\uparrow X$ (due to symmetry reasons)

Sivers fragmentation function



Mulders & Tangerman, NPB 461 (1996) 197

- A nonperturbative $\boldsymbol{k}_T \times \boldsymbol{S}_T$ dependence in the fragmentation process
- Allowed by the symmetries (parity and time reversal)

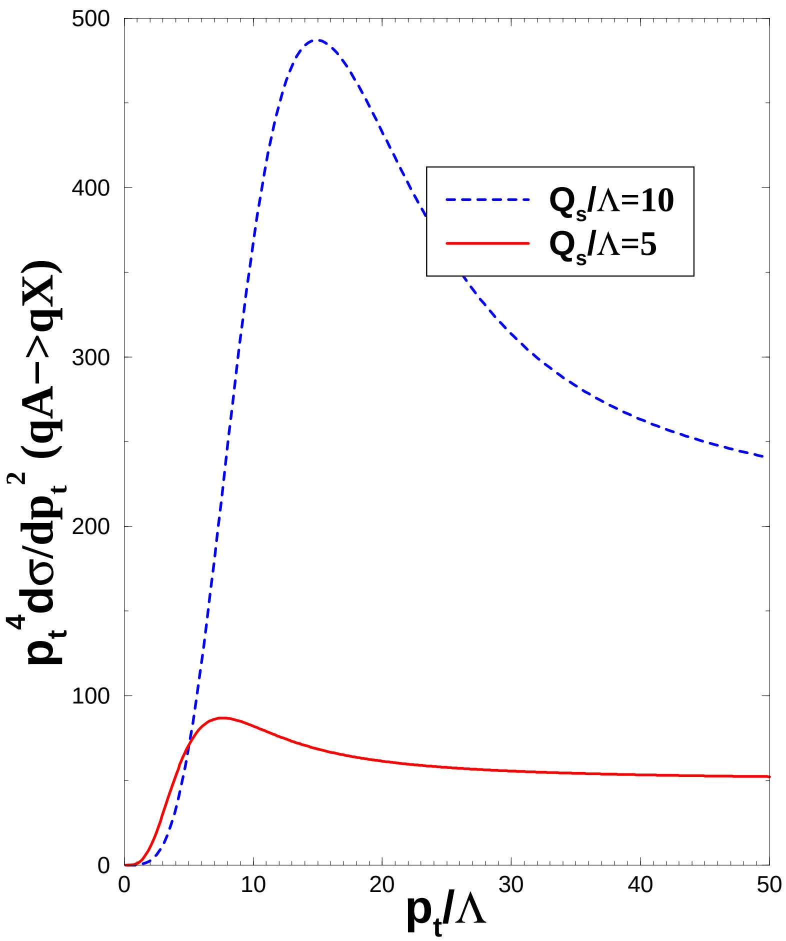
Λ polarization arises in the fragmentation of an *unpolarized* quark

There are strong arguments to believe that $D_{1T}^{\perp}$ is universal (process independent)
Collins & Metz, PRL 93 (2004) 252001

Fits of $D_{1T}^{\perp}$ to data seem reasonable, predictions for SIDIS not tested yet
Anselmino, D.B., D'Alesio & Murgia, PRD 63 (2001) 054029; PRD 65 (2002) 114014

Saturation effects in $p + A \to \Lambda + X$

Asymmetries can also be used to indicate changes in underlying physics



At high p_T, leading twist pQCD predicts:

$$\frac{d\sigma(q\,A \to q\,X)}{d\boldsymbol{p}_T^2} \sim \frac{1}{\boldsymbol{p}_T^4}$$

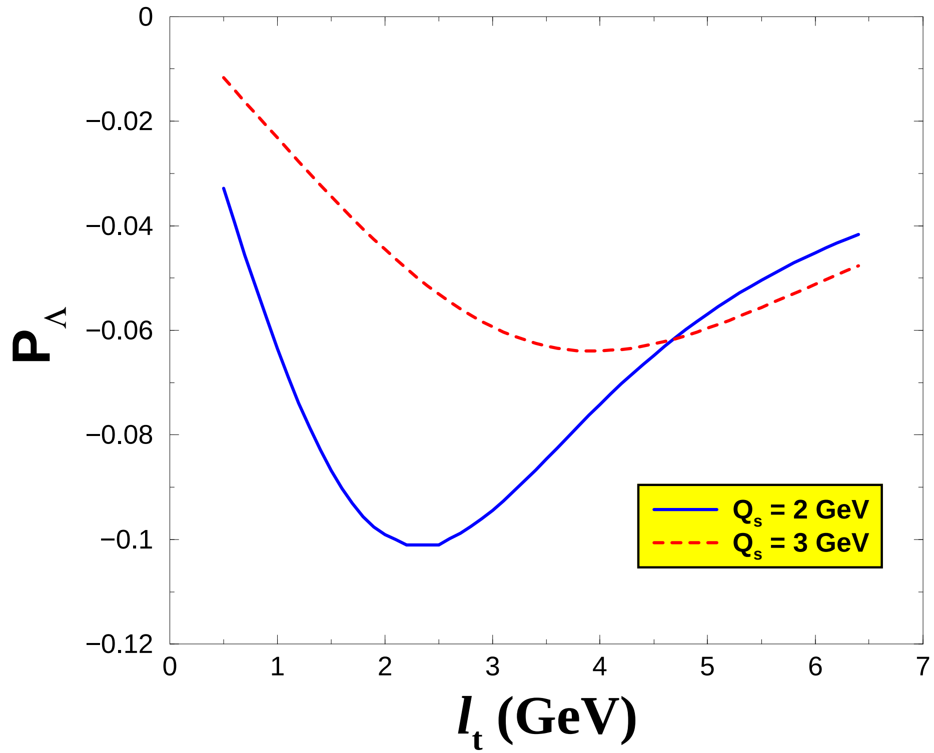
For $p_T \lesssim Q_s$ saturation effects modify the cross section

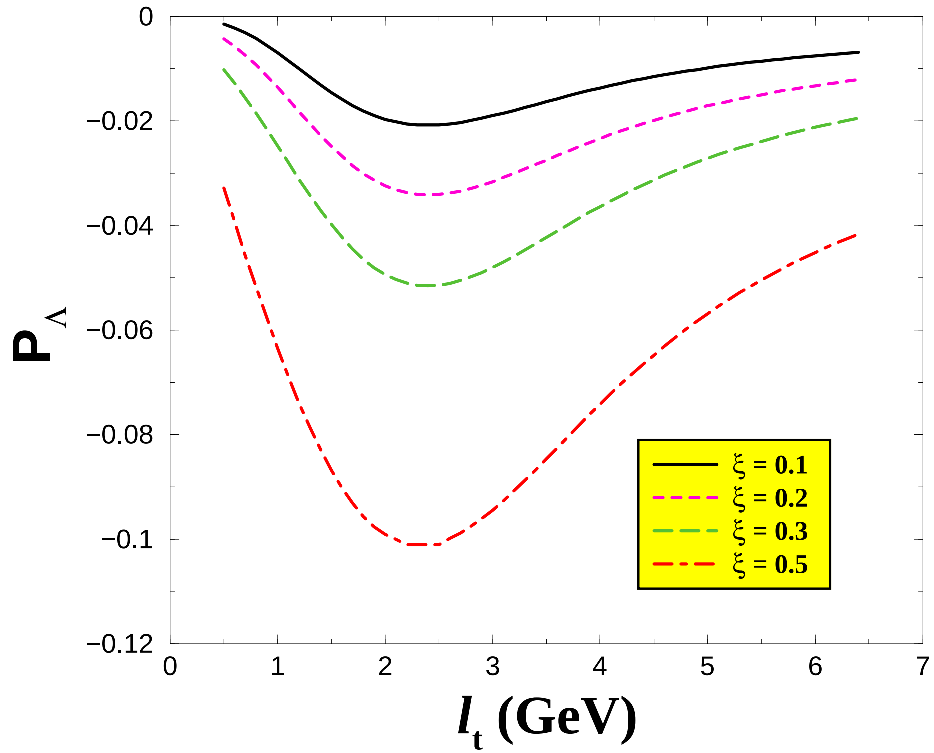
Figure: cross section (times $\boldsymbol{p}_T^4$) in the McLerran-Venugopalan model (large A & $\sqrt{s}$)

Since $D_{1T}^{\perp}$ is $\boldsymbol{k}_T$-odd, it essentially probes the derivative of the partonic cross section

Λ polarization in $p + A \rightarrow \Lambda^{\uparrow} + X$

$p\,A \rightarrow \Lambda^{\uparrow}\,X$: at large A & $\sqrt{s}$ the asymmetry is sensitive to gluon saturation (Q_s)





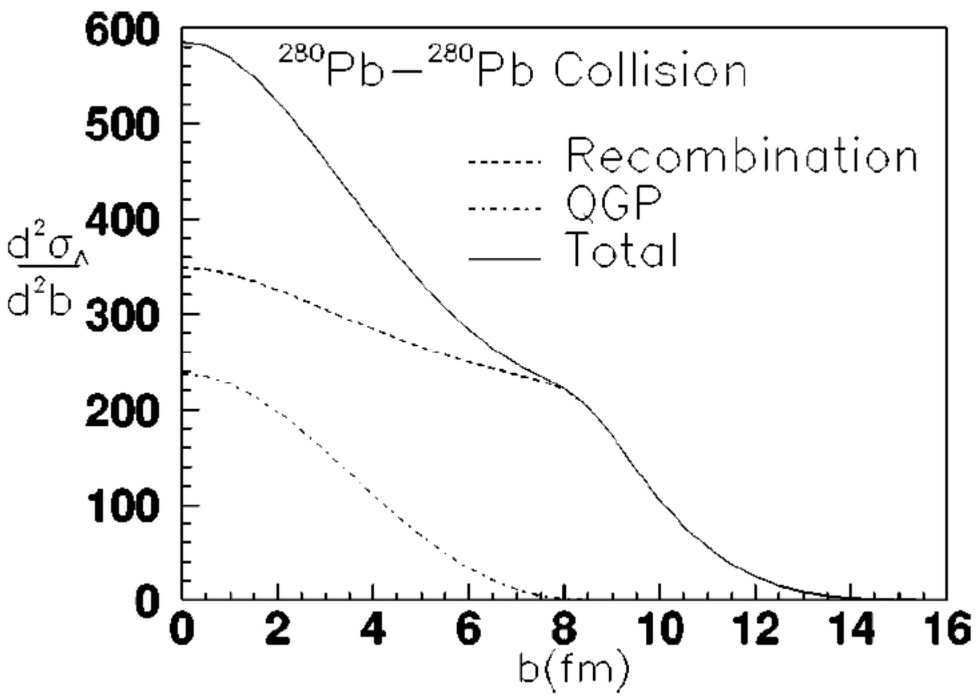
D.B. & Dumitru, PLB 556 (2003) 33

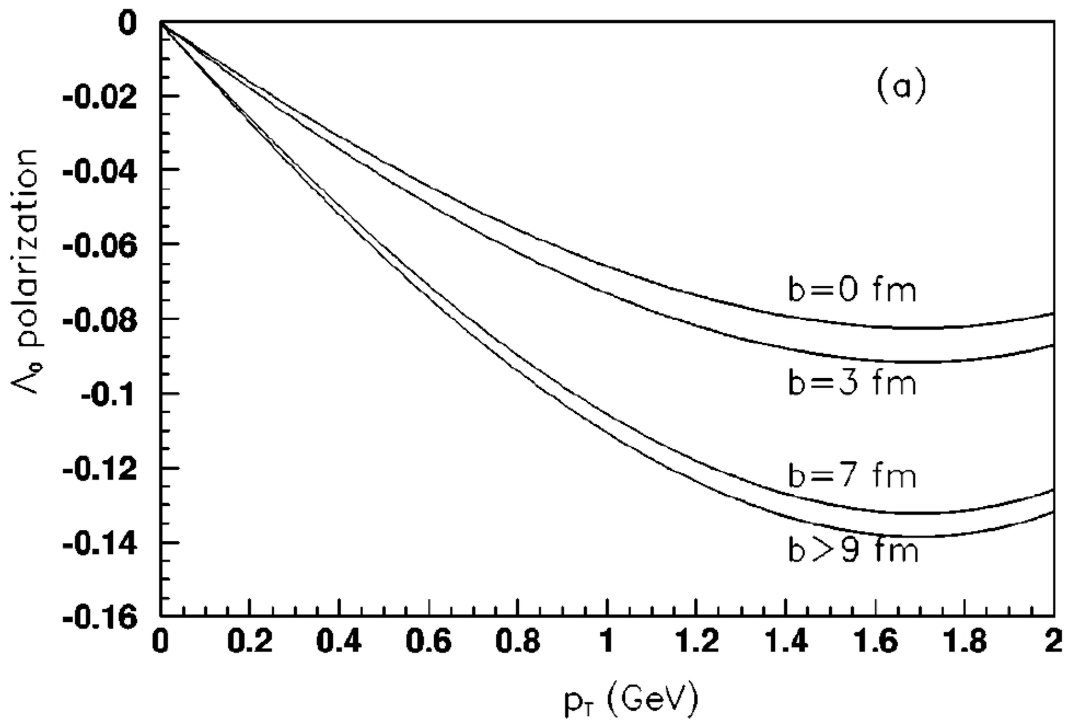
[going beyond classical saturation is in progress]

QGP influence on $A\,A \to \Lambda^{\uparrow}\,X$

If a quark-gluon plasma is formed, then less recombination, so smaller asymmetry

Ayala *et al.* (PRC 65 (2002) 024902): polarization dependence on centrality



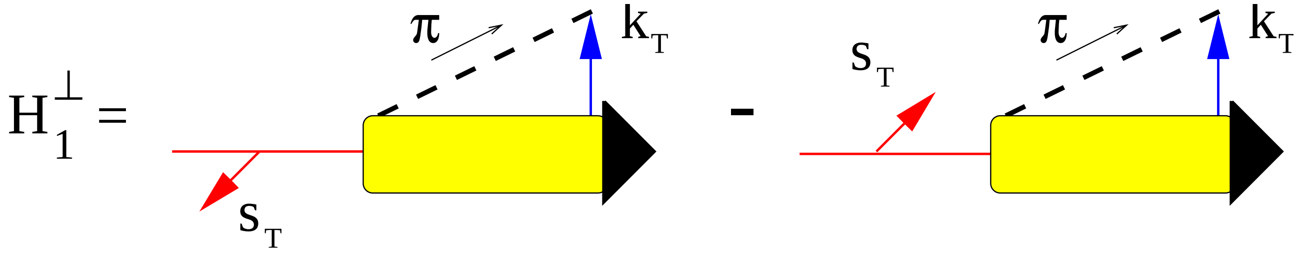


Hence, a full understanding of SSA may turn them into useful tools

Chiral-odd TMDs

Besides $f_{1T}^{\perp}$ and $D_{1T}^{\perp}$, there are two other, equally interesting k_T-odd functions

One is called the Collins fragmentation function:

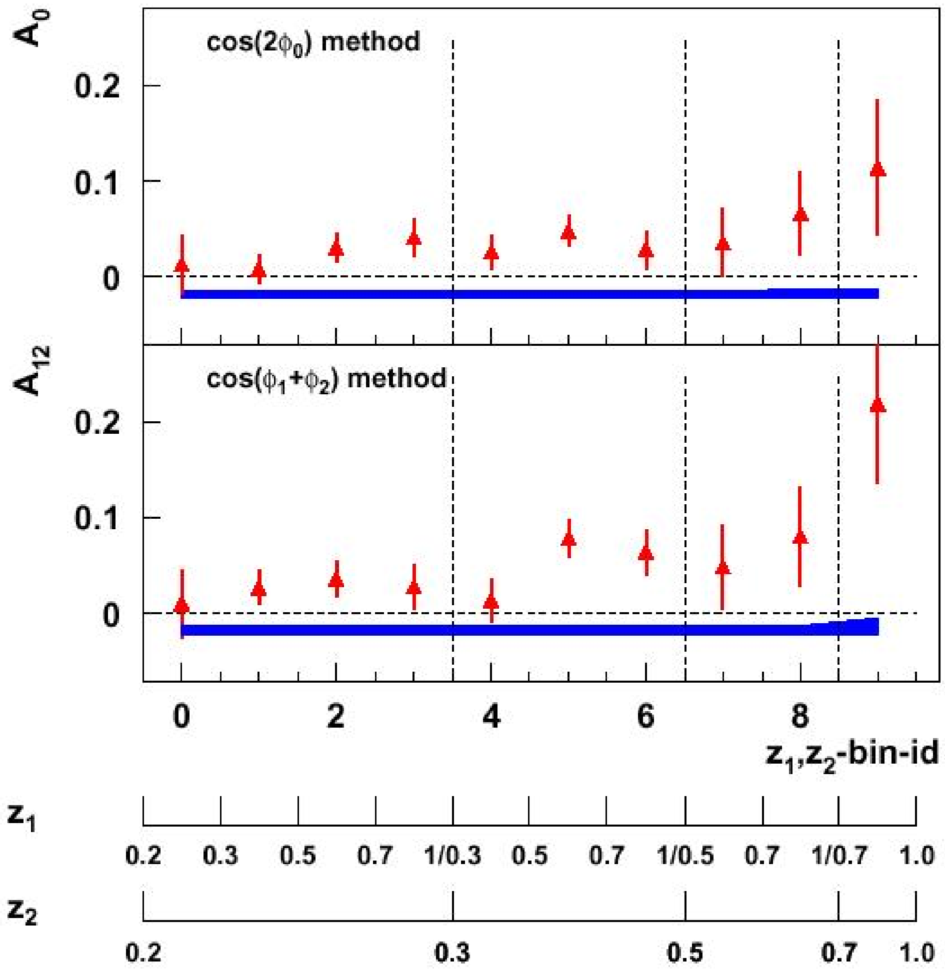


Collins, NPB 396 (1993) 161

It can be extracted from $e^+ \, e^- \to \pi^+ \, \pi^- \, X$: $\langle \cos(2\phi) \rangle \propto (H_1^{\perp})^2$
D.B., Jakob & Mulders, NPB 504 (1997) 345

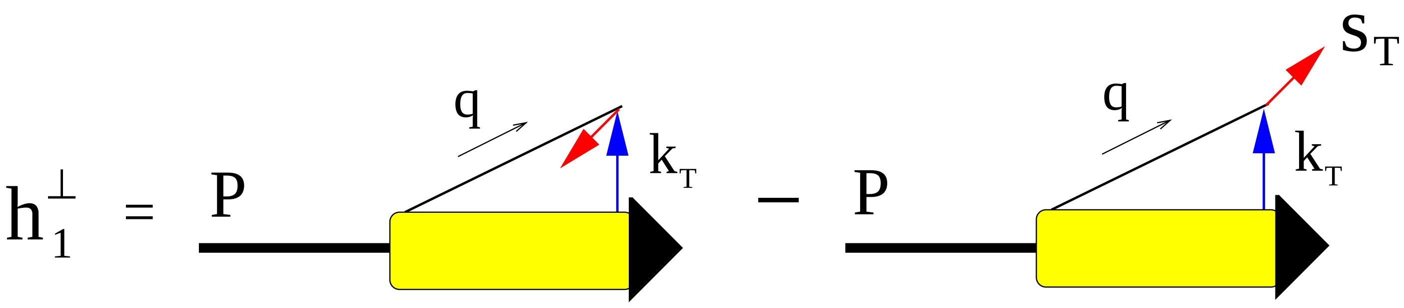
Matthias Grosse Perdekamp (around 2000): use off-resonance BELLE data

Collins asymmetry from BELLE



K. Abe *et al.*, BELLE Collab., hep-ex/0507063, to appear in PRL

Anomalous asymmetry in Drell-Yan



D.B. & Mulders, PRD 57 (1998) 5780

NA10 Collab. ('86/'88) & E615 Collab. ('89) measured the angular distribution of lepton pairs

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} \propto \left(1 + \lambda\cos^2\theta + \mu\sin^2\theta\,\cos\phi + \frac{\nu}{2}\sin^2\theta\cos 2\phi\right)$$

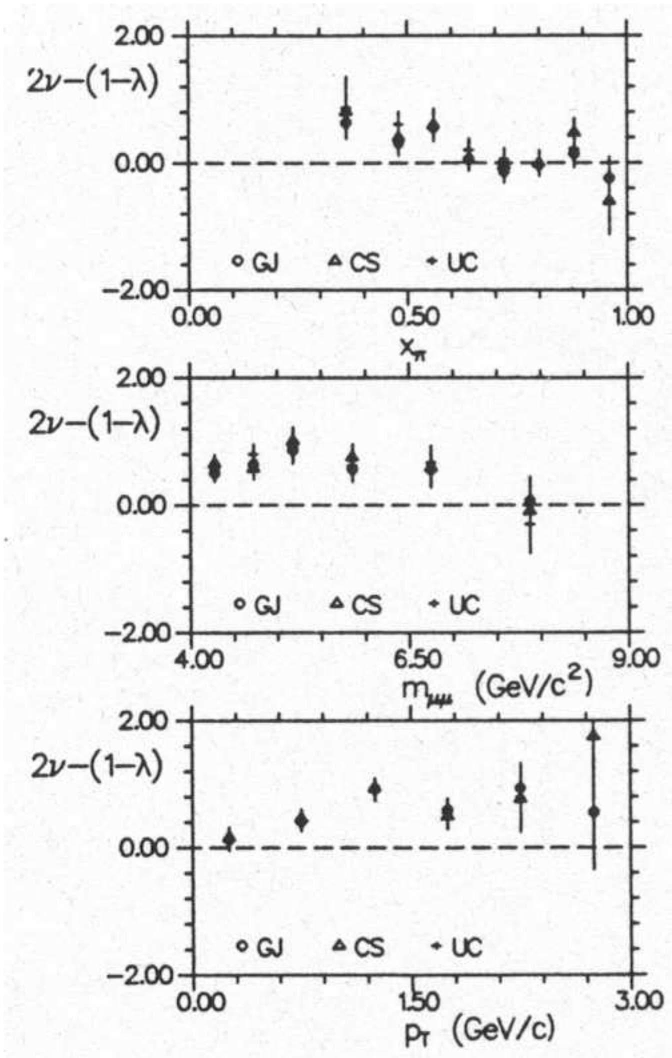
Perturbative QCD relation ($\mathcal{O}(\alpha_s)$): $1 - \lambda - 2\nu = 0$ Lam-Tung relation

Data shows a large deviation from the Lam-Tung relation

Nonzero $h_1^\perp$ offers an explanation of this anomalous Drell-Yan data

D.B., PRD 60 (1999) 014012

* Violation of Lam-Tung relation in Drell-Yan *



Data from NA10 Collab. ('86/'88) & E615 Collab. ('89)

Data for $\pi^- N \to \mu^+ \mu^- X$, with $N = D, W$

$\sqrt{s} \approx 20 \pm 3$ GeV

lepton pair invariant mass $Q \sim 4 - 12$ GeV

NA10: $(1 - \lambda - 2\nu) \approx -0.6$ at $P_T \sim 2 - 3$ GeV

E615: see figure

Large deviation from Lam-Tung relation

Order of magnitude larger & opposite sign w.r.t. $\mathcal{O}(\alpha_s^2)$ pQCD result

Very general conclusions

QCD spin physics is about defining and extracting the appropriate universal nonperturbative quantities

Most of them concern operators nonlocal on and off the lightcone

- For longitudinal proton polarization orbital angular momentum needs to be understood
  Generated the field of GPDs

- For transverse proton polarization spin-orbit coupling effects need to be understood
  Generated the field of TMDs

Relations among the various quantities need to be explored further

Enjoy the rest of the workshop and the World Cup!